Searching for New Physics with Rare B decays

Gino Isidori [*INFN - Frascati*]

- Introduction: flavour physics within & beyond the SM
- What we learned so far: the global picture
- Looking more closely: some *hints* of deviations from the SM
- The *shopping list* of LHCb
- Conclusions

▶ *Introduction: flavour physics within & beyond the SM*

natural...

vs.

...artificial

▶ Introduction: flavour physics within & beyond the SM

Particle physics is described with good accuracy by a simple and *economical* theory:

$$\mathscr{L}_{SM} = \mathscr{L}_{gauge}(A_a, \psi_i) + \mathscr{L}_{Higgs}(\phi, A_a, \psi_i)$$

(Symmetry Breaking)

- *Natural*
- Experimentally tested with high accuracy
- Stable with respect to quantum corrections
- Higly symmetric (*gauge & flavour symmetries*)

- *Ad hoc*
- Necessary to describe data (*clear indication of a non-symmetric vacuum*) but poorly tested in its dynamical form
- Not stable with respect to quantum corrections
- Determine the *flavour structure* of the model

Introduction: flavour physics within & beyond the SM

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$$\mathscr{L}_{\rm eff} = \mathscr{L}_{\rm gauge}(A_a, \psi_i) + \mathscr{L}_{\rm Higgs}(\phi, A_a, \psi_i) + \sum_{d\geq 5} \frac{c_n}{\Lambda^{d-4}} O_n^{(d)}(\phi, A_a, \psi_i)$$

$\mathscr{L}_{\rm SM}$ = renormalizable part of $\mathscr{L}_{\rm eff}$
[= all possible operators with $d \leq 4$ compatible with the gauge symmetry]

operators of $d\geq5$ containing SM fields only and compatible with the SM gauge symmetry

[=most general parameterization of the new (heavy) degrees of freedom, as long as we perform low-energy experiments]

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new sources of flavour-symmtry breaking that we can explore only with low-energy exps.

Two key questions of particle physics today:

- Which is the energy scale of New Physics → High-energy experiments [*the high-energy frontier*]
- Which is the symmetry structure of the new degrees of freedom → High-precision low-energy exp. [*the high-intensity frontier*]

Introduction: flavour physics within & beyond the SM

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Two key questions of particle physics today:

- Which is the energy scale of New Physics → High-energy experiments [*the high-energy frontier*]

Strong theoretical prejudice that some new degrees of freedom appear around or below 1 TeV to stabilise the electroweak symmetry breaking mechanism

Can we reconcile this expectation with the tight constraints of flavour physics ?

$$\mathscr{L}_{\rm eff} = \mathscr{L}_{\rm gauge}(A_a, \psi_i) + \mathscr{L}_{\rm Higgs}(\phi, A_a, \psi_i) + \sum_{d\geq 5} \frac{c_n}{\Lambda^{d-4}} O_n^{(d)}(\phi, A_a, \psi_i)$$

→ 3 identical replica of the basic fermion family [$\psi_i = Q_L, u_R, d_R, L_L, e_R$]

Large global flavour symmetry: $U(1)_L \times U(2)_B \times SU(3)_Q \times SU(3)_U \times SU(3)_D \times \ldots$

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Large global <u>flavour symmetry</u>: $U(1)_L \times U(2)_B \times SU(3)_Q \times SU(3)_U \times SU(3)_D \times \ldots$

→ Flavour-degeneracy broken the Yukawa interaction:

in the quark sector:

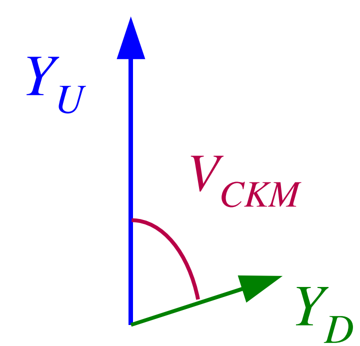
$$\bar{Q}_L^i Y_D^{ik} d_R^k \phi \rightarrow \bar{Q}_L^i M_D^{ik} d_R^k$$

$$\bar{Q}_L^i Y_U^{ik} u_R^k \phi_c \rightarrow \bar{Q}_L^i M_U^{ik} u_R^k$$

$$M_D = \mathrm{diag}(m_d, m_s, m_b)$$

$$M_U = V \times \mathrm{diag}(m_u, m_c, m_t)$$

→ <u>The CKM matrix</u>



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... while we still have a rather limited knowledge of the flavour structure of the new degrees of freedom (which hopefully will show up around the TeV scale)

We have some favourite scenarios, such as

MFV = *assumption that the SM Yukawa couplings are the only non-trivial flavour-breaking terms also beyond the SM*

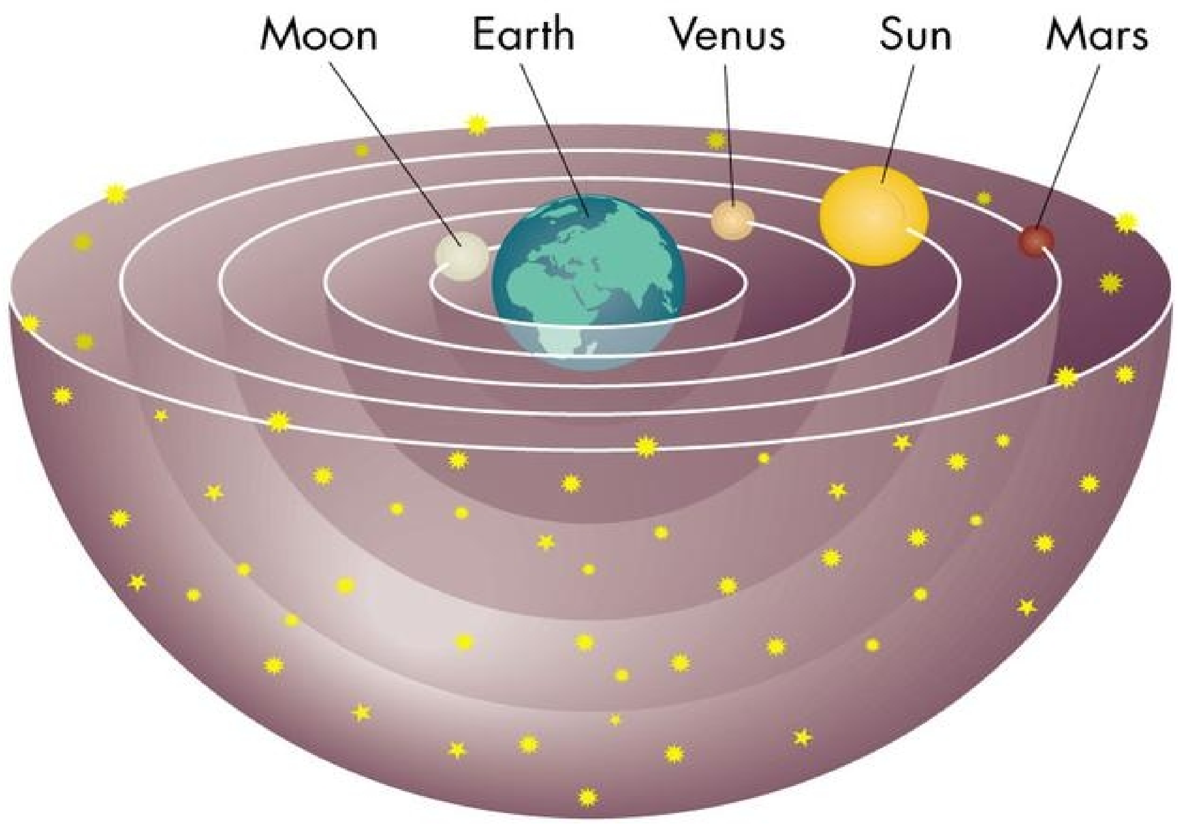
D'Ambrosio *et al.* '02

However, at this stage these are still theoretical speculations, far from being clearly established from data

The main goal of flavour physics is trying to understand if there are additional non-trivial flavour breaking terms beside the SM Yukawas

What we learned so far: the global picture

The SM is very successful in describing quark-flavour mixing !



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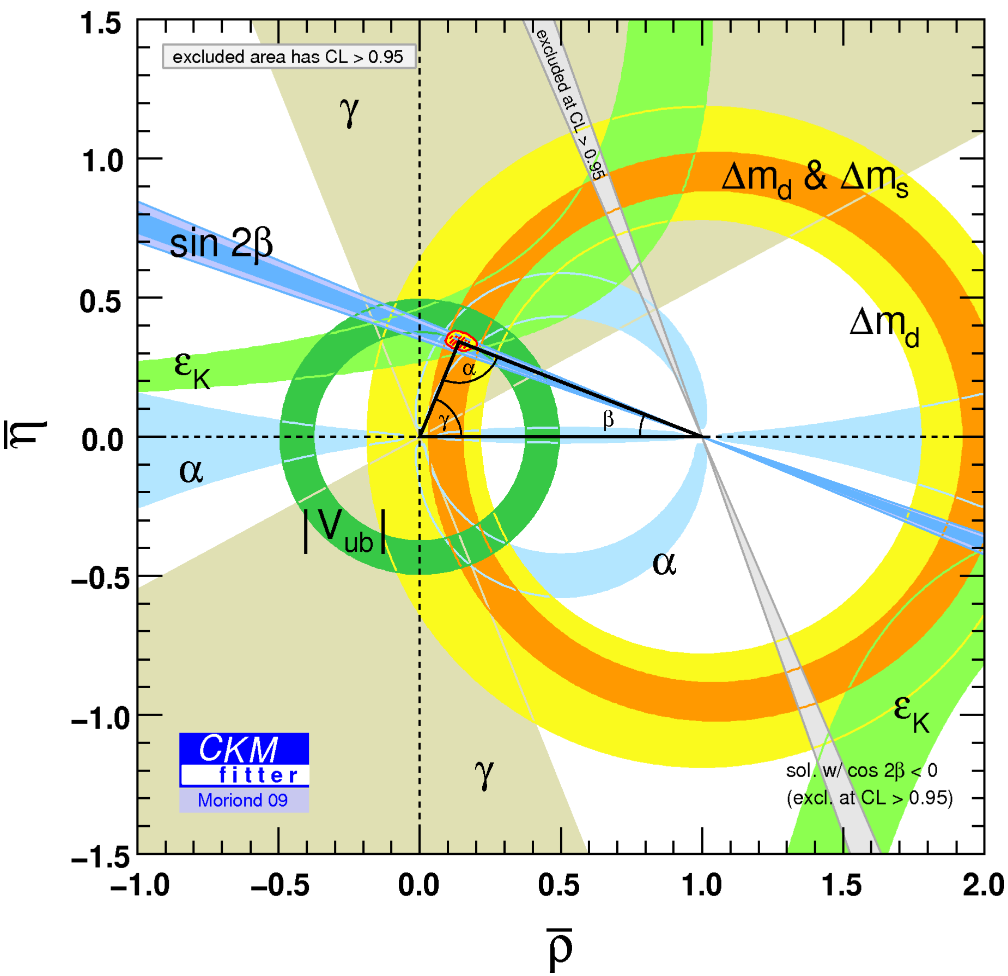
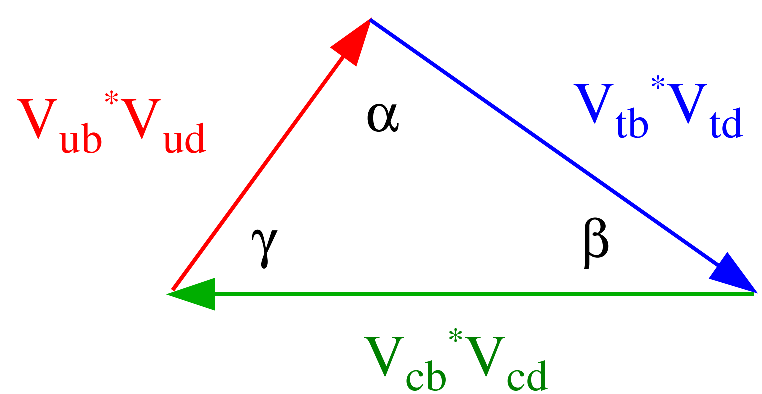
Good consistency of the experimental constraints appearing in the so-called CKM fits [slight tension between sin(2β) and V_{ub}, not very significant yet]



$$V_{CKM} V^{+}_{CKM} = I$$

triangular relation:

$$V_{ub}{}^{*} V_{ud} + V_{cb}{}^{*} V_{cd} + V_{tb}{}^{*} V_{td} = 0$$



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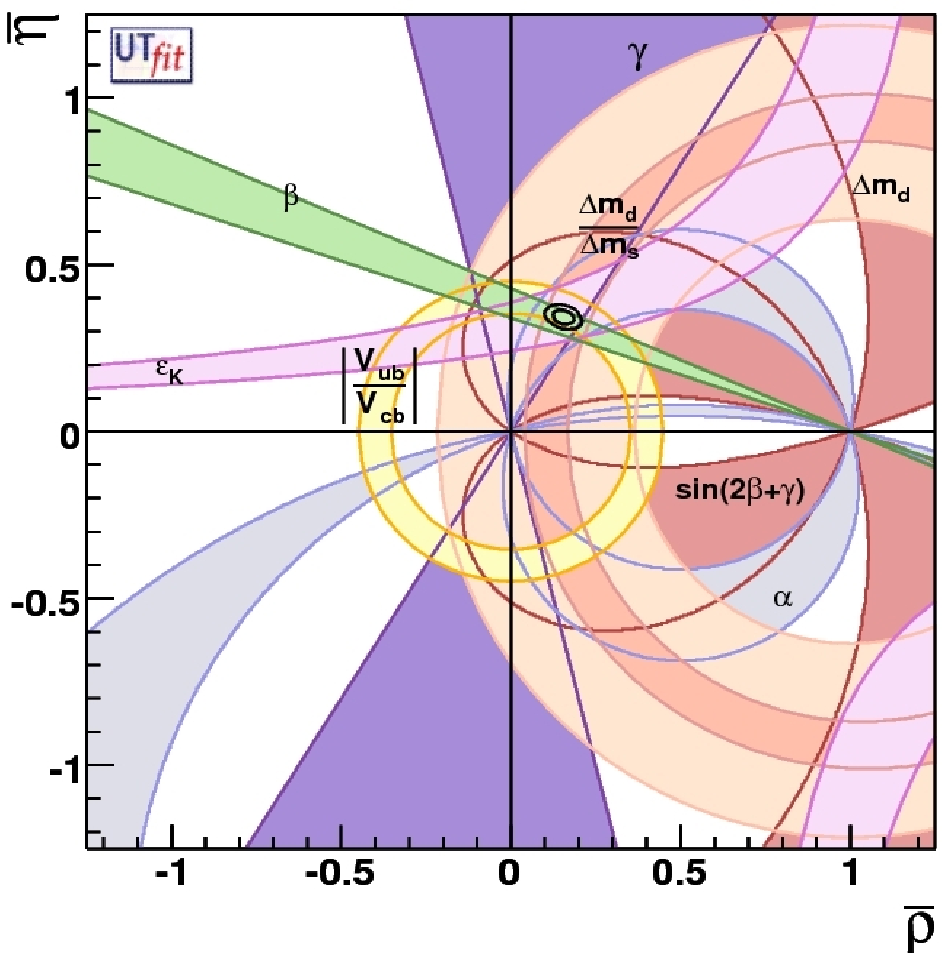


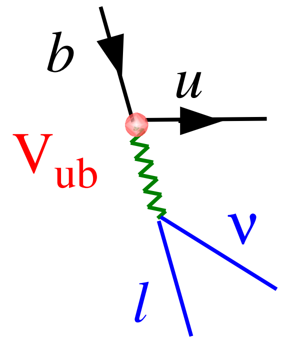
- Changing statistical treatment does not lead to significant differences: high-quality data are finally drawing the picture…!

- There is much more, not shown in such fits, which confirm the good success of the SM in describing flavour mixing

I. The CKM fits [constraints in the ρ-η plane]

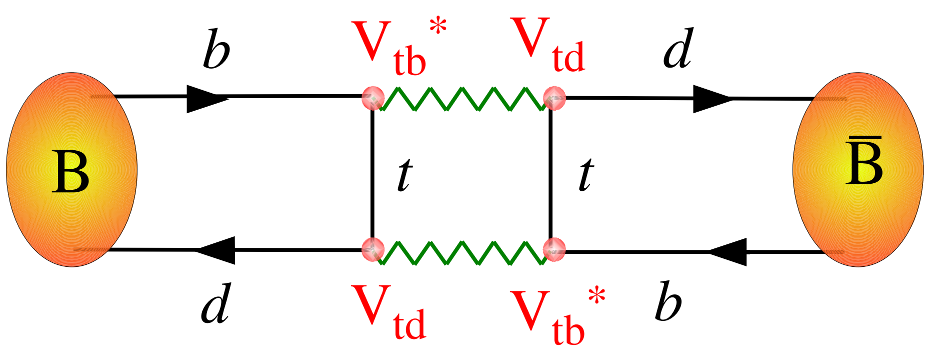
The most remarkable aspects of such fits is the consistency between tree-level constraints on the CKM matrix and those of ΔF=2 observables:

Tree-level semilptonic decays



vs.

ΔF =2 neutral-meson mixing

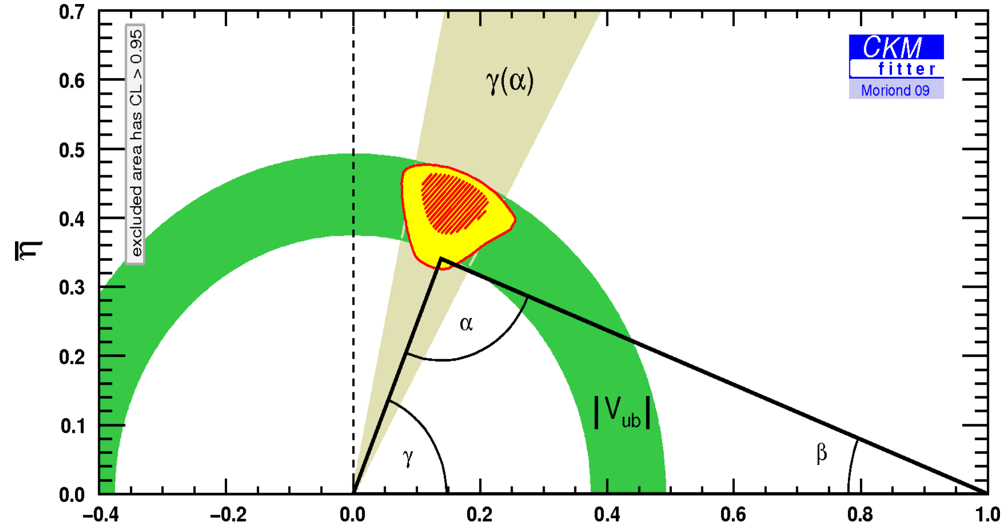


$$\rightarrow \frac{(y_t V_{tb}^{*} V_{td})^2}{16\,\pi^2 M_W^{\,2}}$$

Highly suppressed amplitude potentially more sensitive to New Physics

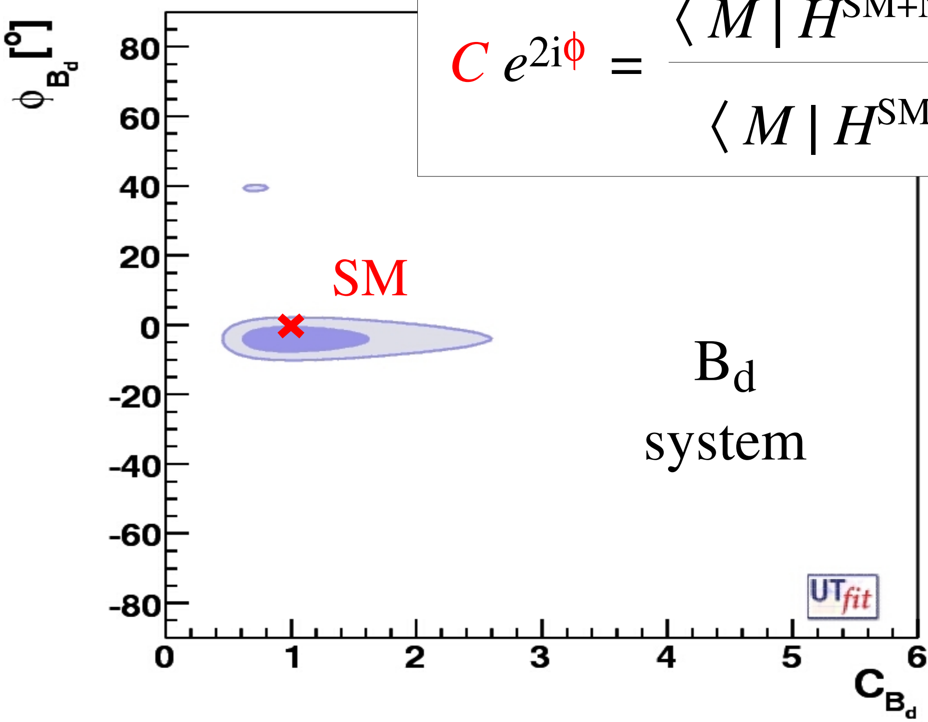
I. The CKM fits [constraints in the ρ-η plane]

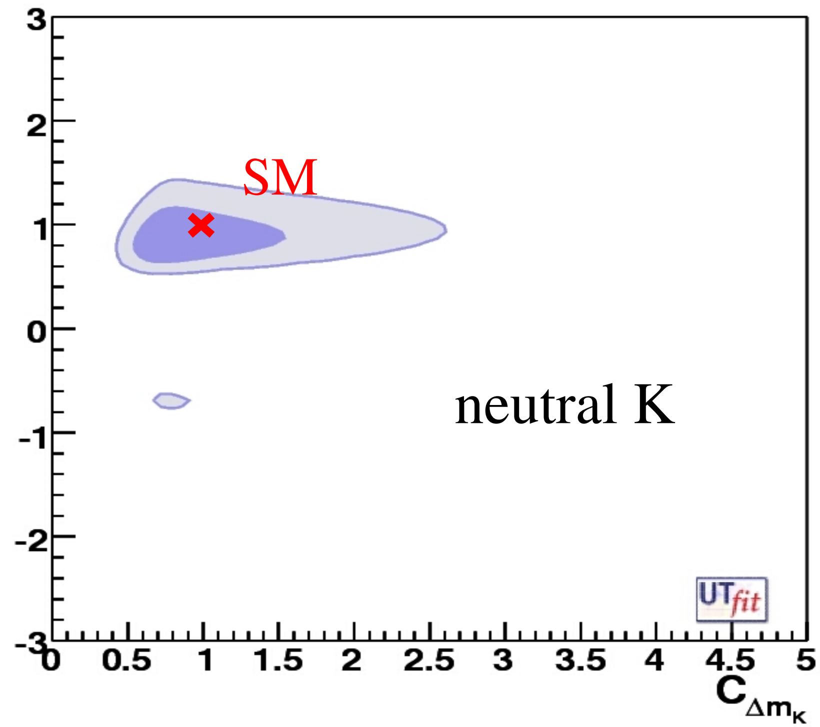
CKM unitarity triangle using only tree-level dominated amplitudes →



General fit of NP in ΔF=2 amplitudes

$$C\, e^{2i\phi} = \frac{\langle M \,|\, H^{\mathrm{SM+NP}} \,|\, \bar{M} \rangle}{\langle M \,|\, H^{\mathrm{SM}} \,|\, \bar{M} \rangle}$$





I. The CKM fits [constraints in the ρ-η plane]

These results are quite instructive if interpreted as bounds on the scale of new physics:

$$M(B_d\text{-}\bar{B}_d) \sim \frac{(V_{tb}{}^* V_{td})^2}{16\,\pi^2 M_W{}^2} + c_{NP}\,\frac{1}{\Lambda^2}$$

← contrbution of the new heavy degrees of freedom

c_{NP}:

- ~ 1 — tree/strong + generic flavour → $\Lambda \gtrsim 2\times10^4$ TeV [K]
- $\sim 1/(16\,\pi^2)$ — loop + generic flavour → $\Lambda \gtrsim 2\times10^3$ TeV [K]
- $\sim (V_{ti}{}^* V_{tj})^2$ — tree/strong + MFV → $\Lambda \gtrsim 5$ TeV [K & B]
- $\sim (V_{ti}{}^* V_{tj})^2/(16\,\pi^2)$ — loop + MFV → $\Lambda \gtrsim 0.5$ TeV [K & B]

MFV (or something very similar at least for $s\to d$ & $b\to d$),
is mandatory if we want to keep Λ in the TeV range

II. Rare decays

Good agreement with SM expectations is found also in rare FCNC $\Delta F=1$ decays.
Most remarkable example: $B \to X_s \gamma$

Most accurate SM th. estimate:

$$\mathcal{B}(B \to X_s\gamma) = (3.15 \pm 0.23)\times 10^{-4}$$

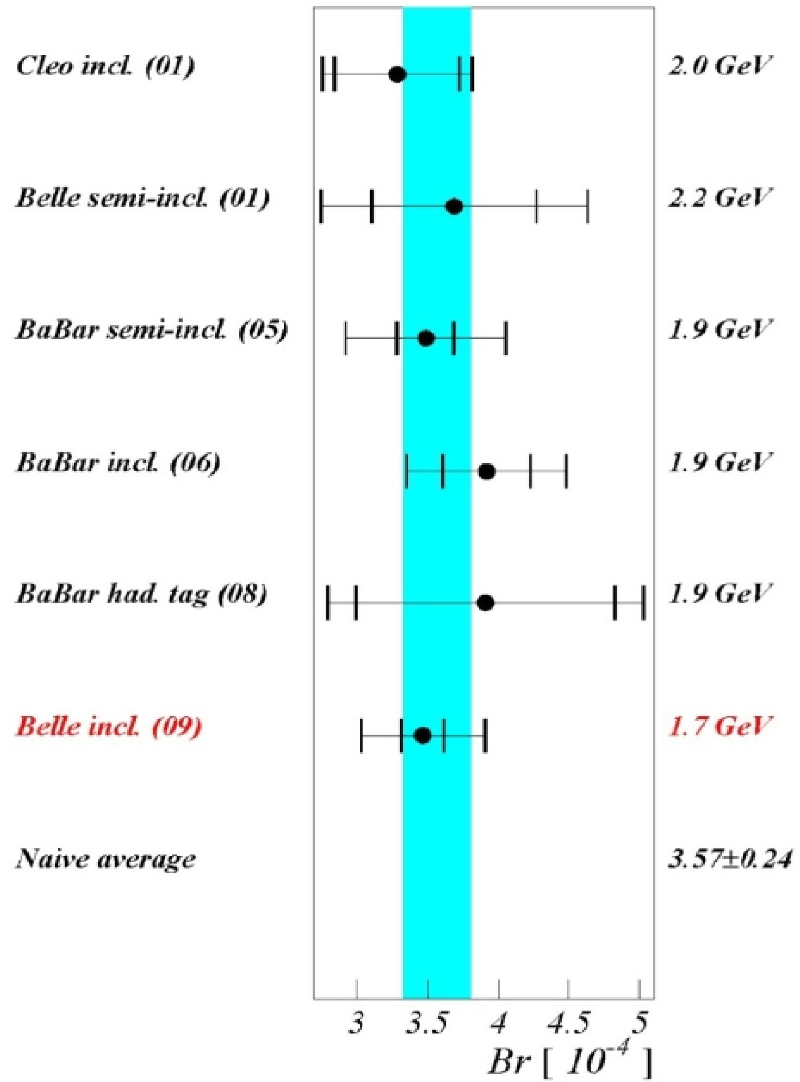
[Misiak *et al.* '07]

- NNLO perturbative calculation
- Inclusive non-pert. effects using HQET
- E_γ cut controlled by shape-function analysis
- Hard (impossible ?) to improve further in the near future...

To be compared with:

$$\mathcal{B}(B \to X_s\gamma) = (3.57 \pm 0.24)\times 10^{-4}$$

[2009 exp. WA]



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One of the most significant constraint in many SM extensions (*with MFV as stringent as EW precision observables*)

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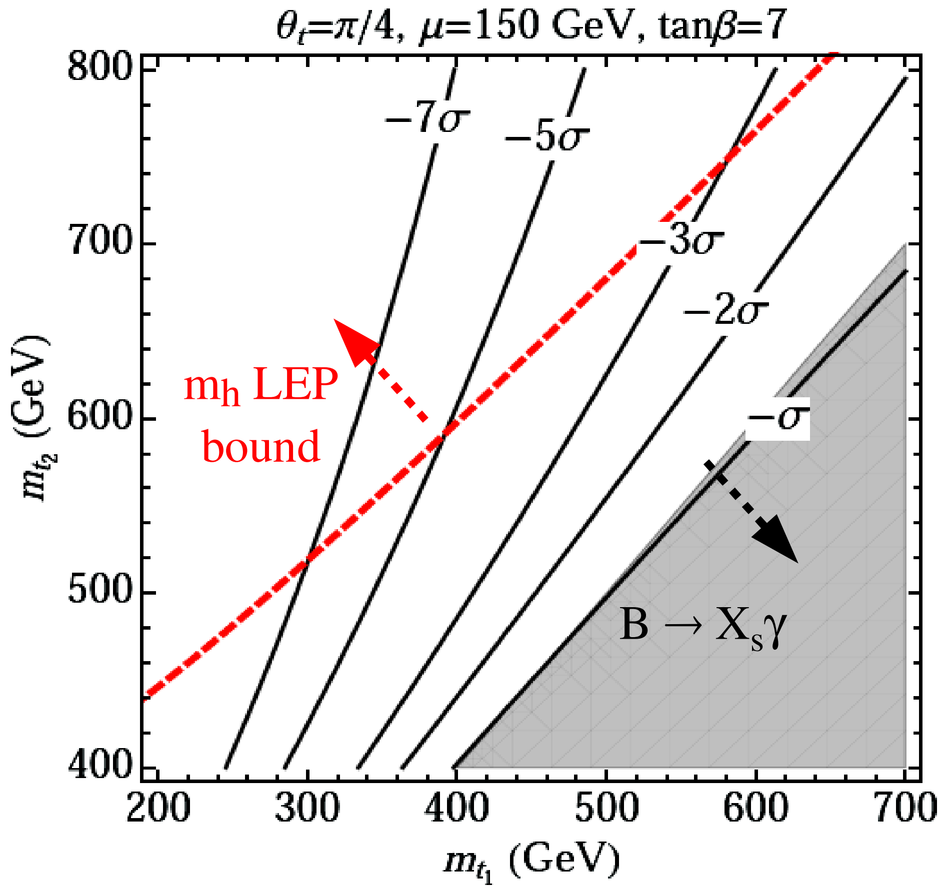
E.g.: *contraints on the stop sector of the MSSM* [with MFV & heavy gauginos]



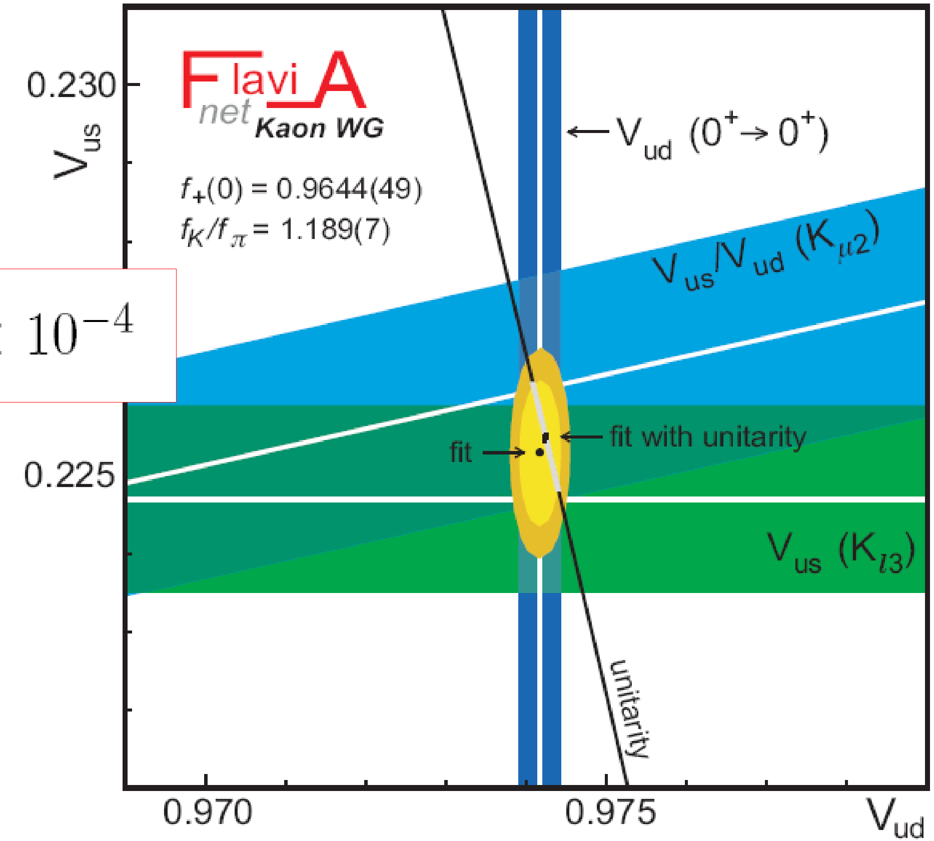
Barbieri & Pappadopulo '09

III. Vus & CKM Unitarity

An impressive progress has been obtained also in testsing charged-current interactions:

$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 - 1 \;=\; (-1 \pm 6) \times 10^{-4}$$

few 0.1% error !



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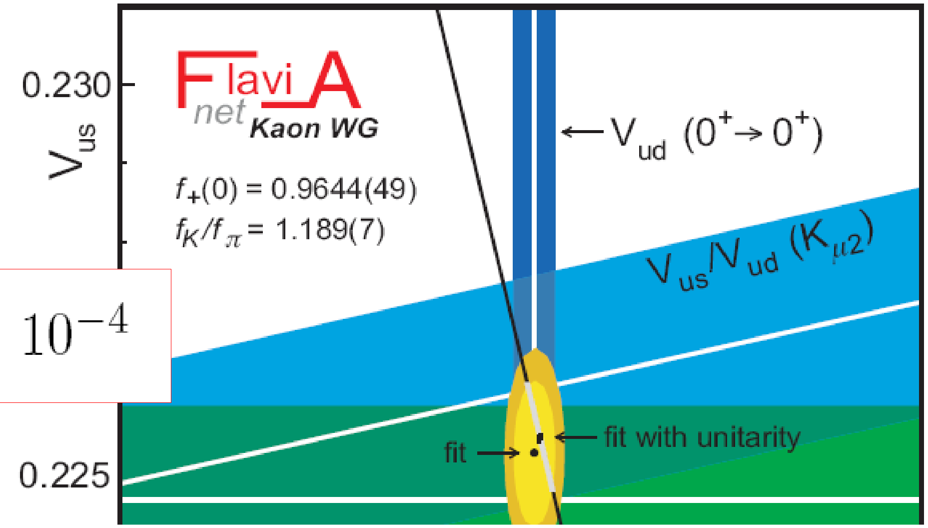


↓

Very challenging for all extensions of the SM predicting some breaking of universality between quarks & leptons (*strong e.w. symm. breaking*, *extra dim*....)

$$\mathscr{L}_{\text{c.c.-eff.}} = G_F^{CKM} (\bar{U}_L \gamma_\mu D_L)(\bar{l}_L \gamma_\mu \nu_L) + G_F^{(\mu)} (\bar{\nu}_L \gamma_\mu l_L)(\bar{l}_L \gamma_\mu \nu_L) + \ldots$$

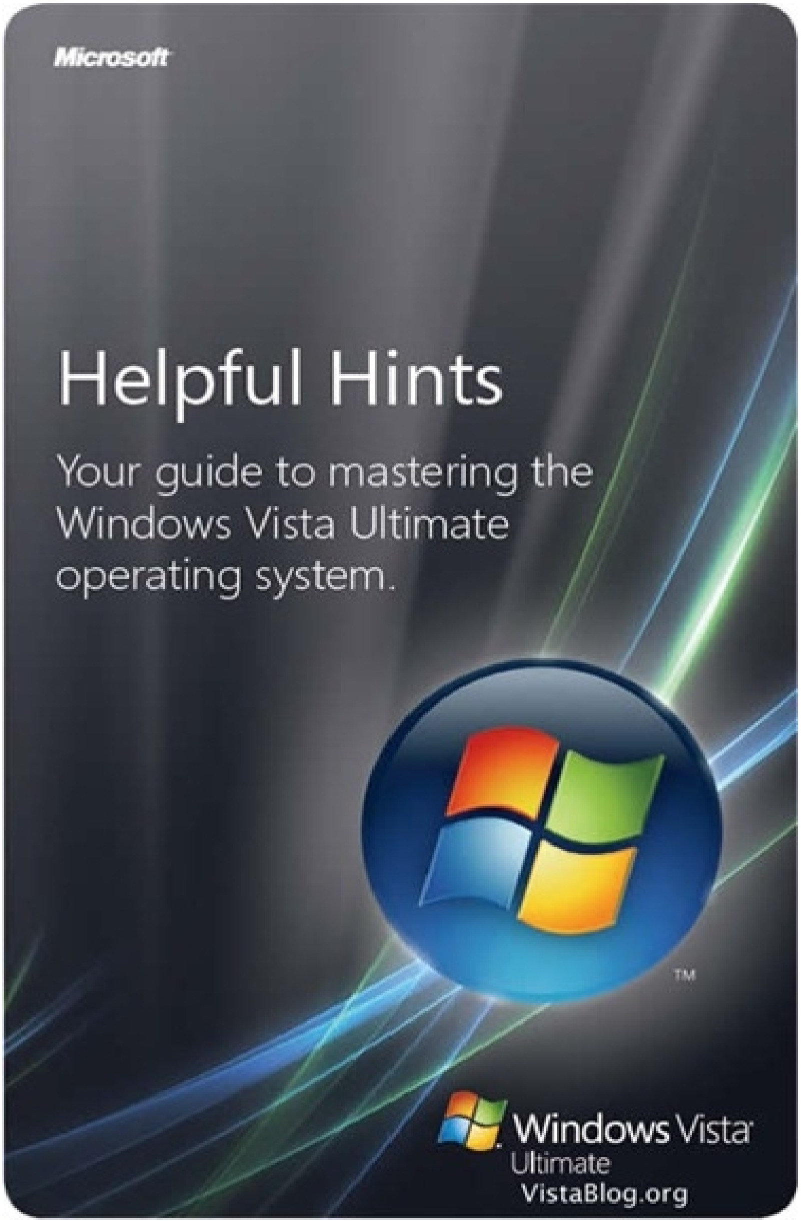
$$G_F^{CKM} = G_F^{(\mu)} [\, |V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 \,]^{(1/2)}$$

$$G_F^{CKM} - G_F^{(\mu)} = \frac{c^{(i)}}{\Lambda^2}$$

bounds on Λ of several TeV

See e.g. Cirigliano *et al.* '09

▶ *Looking more closely: some "hints" of deviations from the SM*



Looking more closely: some "hints" of deviations from the SM

There are a few observables where the agreement with the SM is not so good, such as

- $A_{FB}(B\to K^* l^+ l^-)$, CPV in B_s mixing, $B\to\tau\nu$
- Non-leptonic direct CPV in $B\to K\pi$ (the so-called "$B\to K\pi$ *puzzle*")
- Time-dependent CPV in $b\to s$ penguin modes

But we are still far from claiming serious discrepancies either because of limited statistics, or because of uncontrolled/underestimated theory errors, or because of both...

I. $A_{FB}(B\to K^* l^+ l^-)$

$$A_{FB} = \int \frac{d^2 B(B\to K^* \mu^+ \mu^-)}{d\cos\theta}\, sgn(\cos\theta) \;\propto\; \mathrm{Re}\{ C_{10}^* [q^2 C_9^{eff}(q^2) + r(q^2) C_7] \}$$

θ = angle between μ^+ & B in the dilepton rest frame

q^2 = dilepton invariant mass

C_7: γ penguin [dipole] ⇔ b→sγ

C_9^{eff}: γ peng. [vector] + (Z & box)

C_{10}: Z peng. + box [axial]

- Interference of axial & vector currents ⇒ direct access to the *relative phases* of the Wilson coefficients
- Uncertainties of hadronic form factors under control in the low-q^2 region (pQCD, sum-rules)

Beneke, Feldmann, Seidel '01

⇓

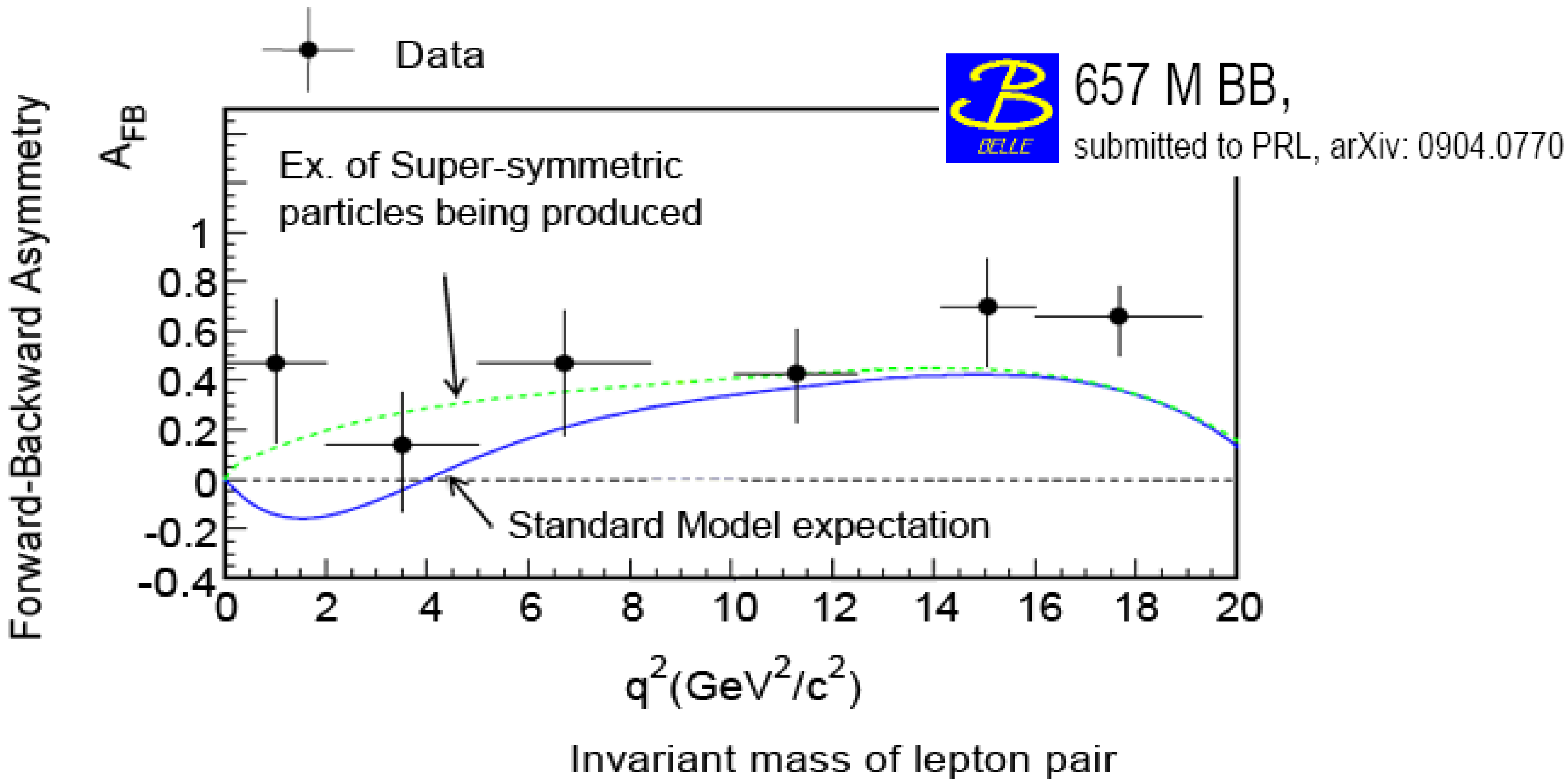
Sensitive test of various realistic extensions of the SM (e.g. non-standard Zbs effective coupling)

Ali *et al.* '00; Buchalla *et al.* '01

[...] Altmannshofer *et al.* '09

I. $A_{FB}(B \to K^* l^+ l^-)$

Belle has just reached an interesting sensitivity on this observable:



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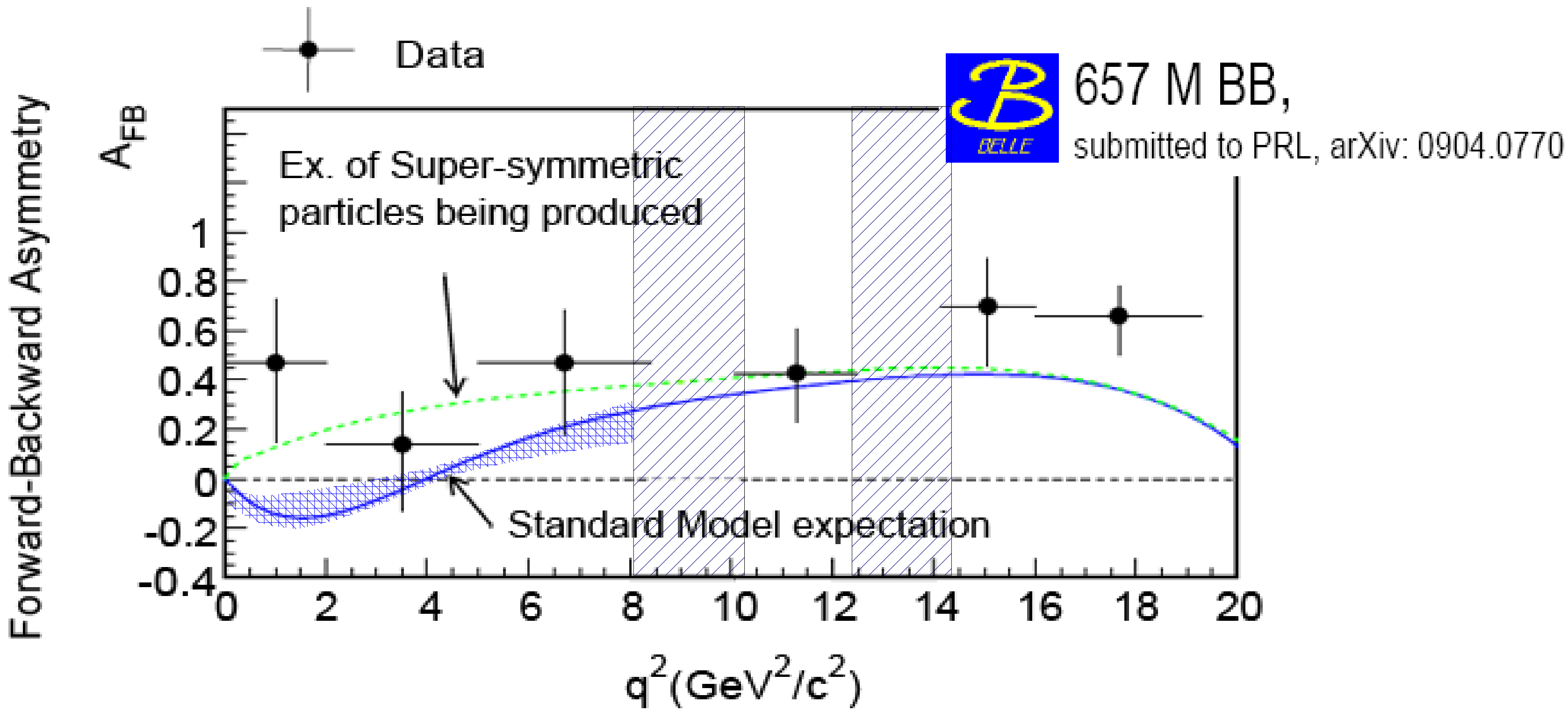

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LHCb will find out if the discrepancy is serious...

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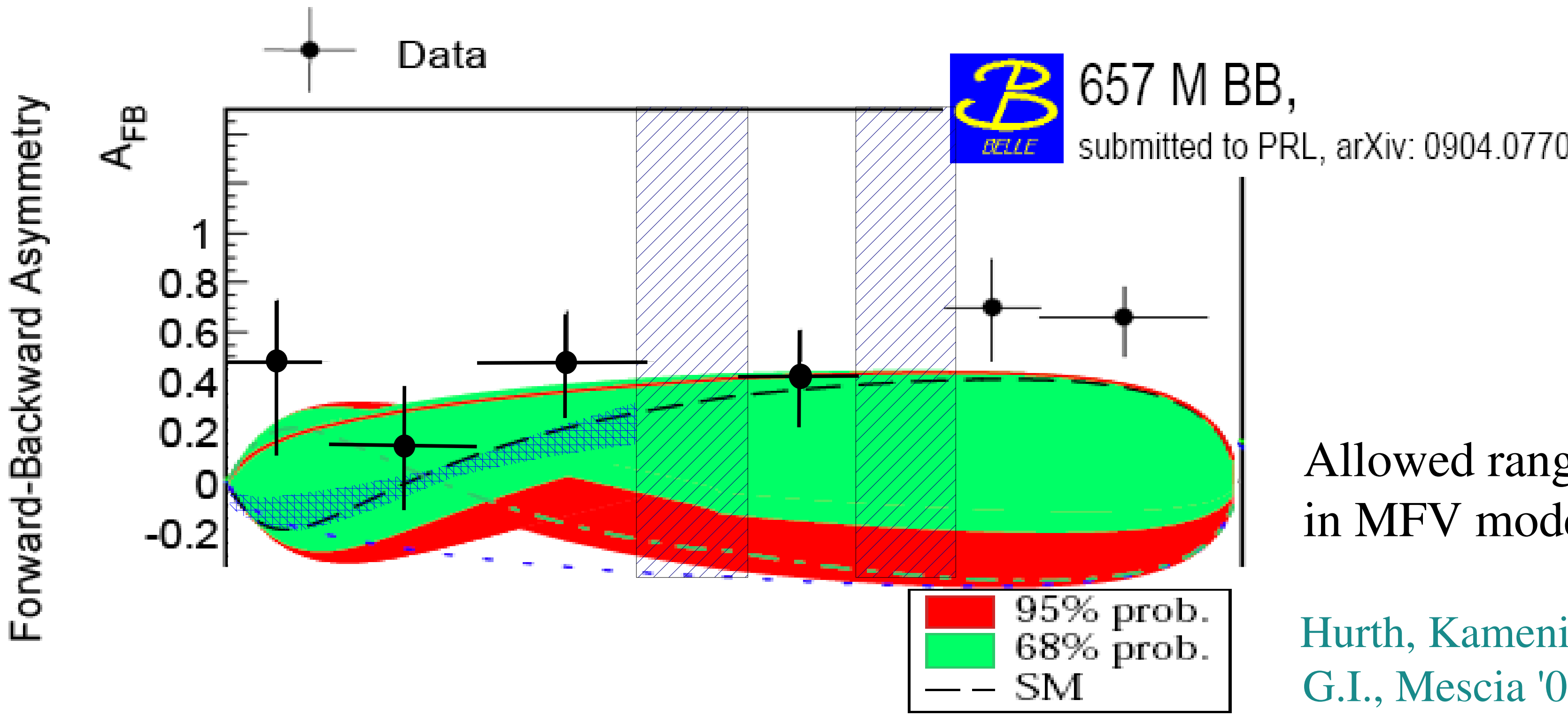

Allowed range in MFV models

Hurth, Kamenik
G.I., Mescia '08

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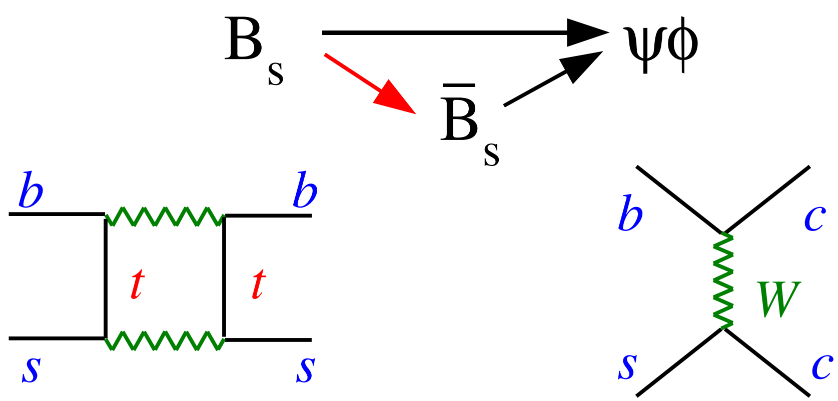
II. CPV in B_s mixing

The weak phase of B_s mixing is the last missing ingredients about down-type $\Delta F=2$ transitions [K, B_d, B_s]: a key element to understand if there is room for new sources of flavour symmetry breaking.

Theoretical clean extraction via $B_s \to \psi\phi$ [$b+s \to ccs+s$]



Experimentally quite challenging:

- Fast oscillations
- Non-trivial angular analysis
- Simultaneous fit of $\Delta\Gamma_s$ and the mixing phase

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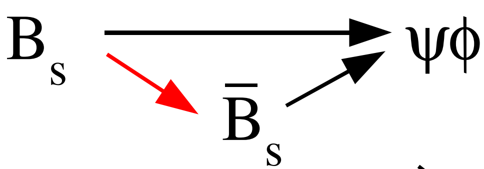
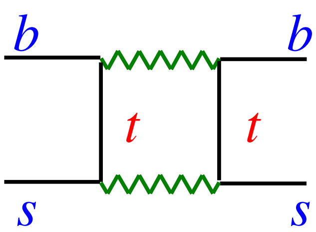
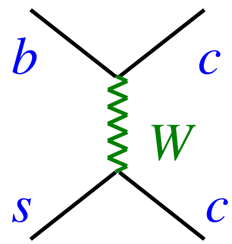
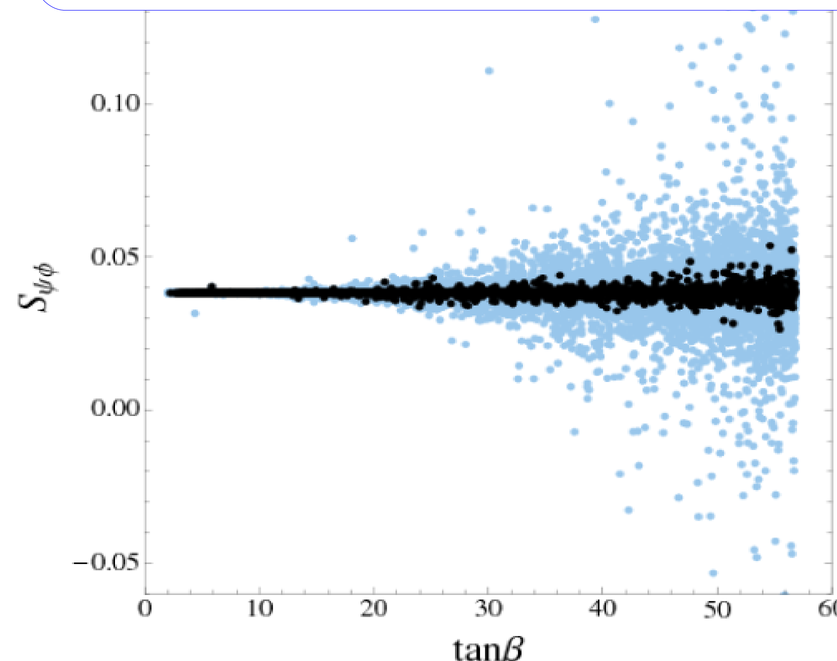






A non-zero CP asym. in $B_s \to \psi\phi$ rules out both SM and MFV



Buras *et al.* '09

Experimentally quite challenging:

- Fast oscillations
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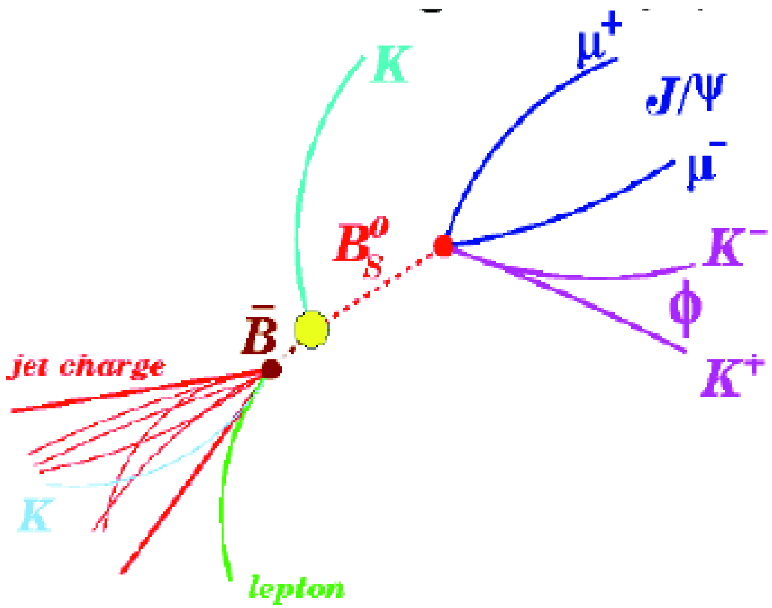
II. CPV in B_S mixing

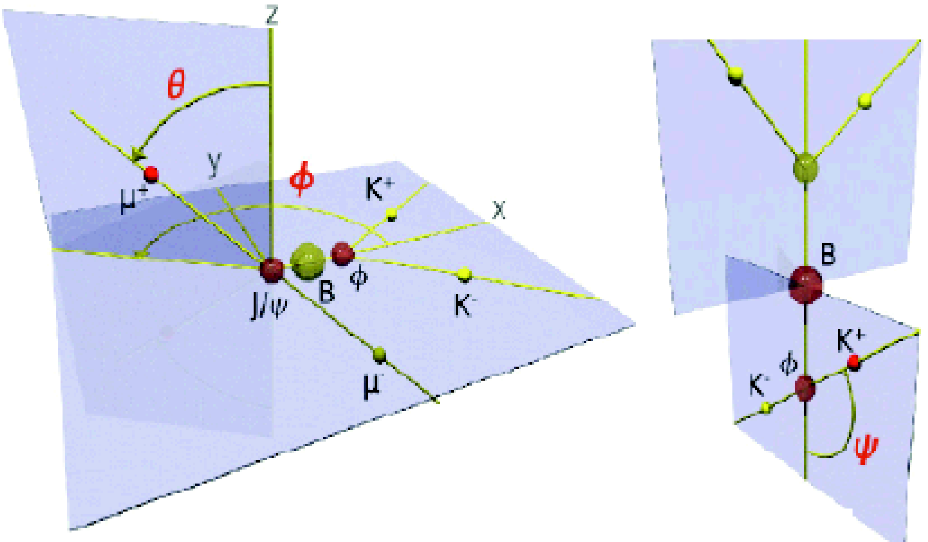
1. Reconstruct decays from stable products:
   - $B_s \to J/\Psi[\mu^+\mu^-]\ \Phi[K^+K^-]$
   - $B_d \to J/\Psi[\mu^+\mu^-]\ K^{*0}[K^+\pi^-]$ (control sample)



2. Measure lifetime $ct = m_B * L_{xy}/p_T$
   - Proper time resolution essential to resolve oscillations

3. Measure decay angles in transversity base:

$$\vec{w} = (\vartheta, \phi, \psi)$$



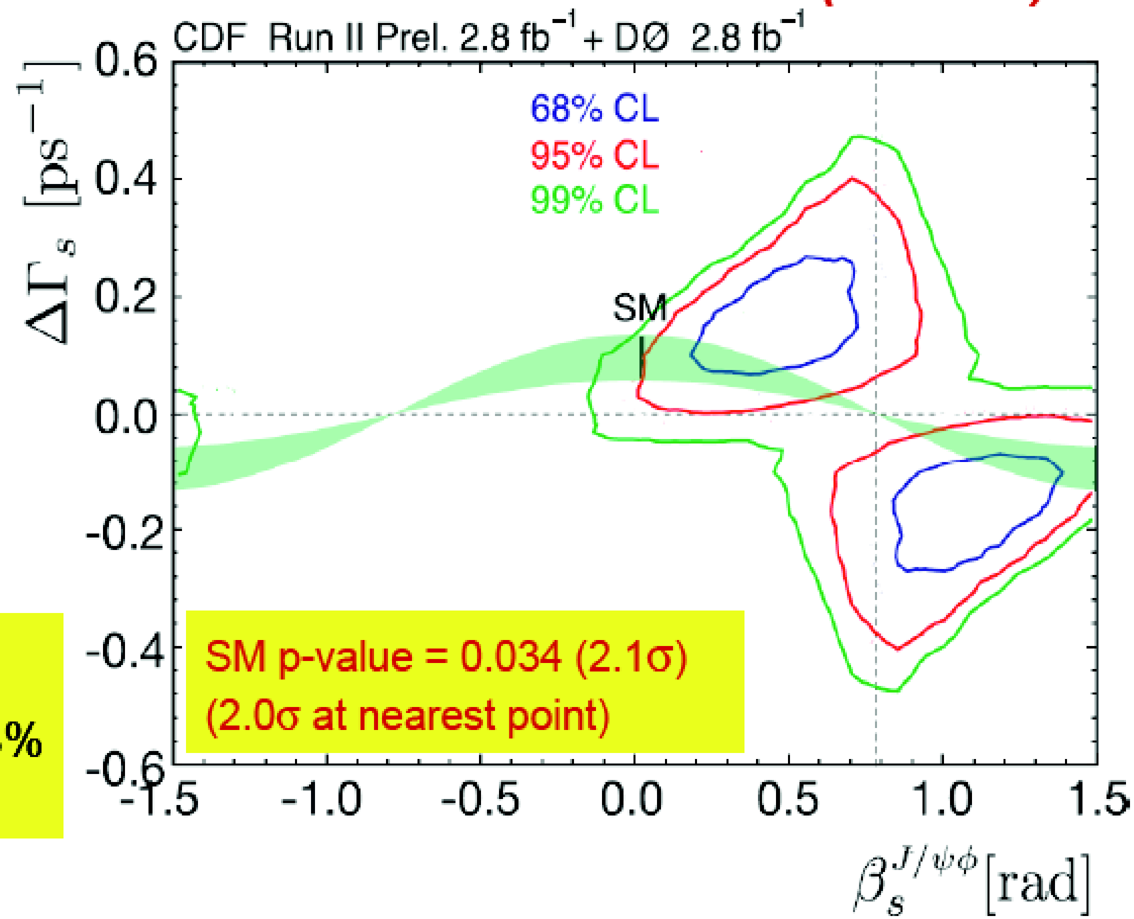
4. Identify Bs flavor at production time:
   - Flavor Tagging (Tag decision ξ)

5. Perform maximum likelihood fit:
   - Likelihood in m, ct, w , ξ

G. Punzi, EPS 2009

Combined Tevatron result *(NEW)*

- Full inclusion of systematics and non-Gaussian effects
- No constraints. Make available to combination groups.



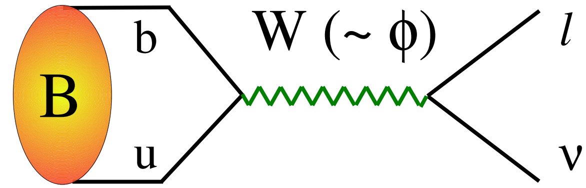
$\beta_s^{J/\psi\phi}$ range:
[0.27,0.59] U [0.97,1.30] @68%
[0.10,1.42] @95%

- Compared to HFAG 2008:
  Larger CDF sample + Better accounting for tails ⇒ same level of SM agreement.
- Both CDF and D0 currently working on **2x** samples.
- Expect improved precision by ***simultaneous fit*** of CDF and D0 samples.

G. Punzi, EPS 2009

III. $B(B \to \tau \nu)$

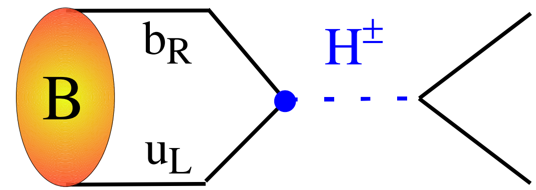
The helicity suppression of the SM amplitude makes $B \to \tau\nu$ an excellent probe of models with 2 Higgs doublets (such as the MSSM):



longitudinal comp. of the W

$$B(B \to l\,\nu) = B_{SM} \left(1 - \frac{m_B^2 \tan\beta^2}{M_H^2 (1 + \epsilon_0 \tan\beta)} \right)^2$$

B_{SM} ↑ $C_0\, f_B^2\, |V_{ub}|^2$



extra tree-level contribution
simple M_H & $\tan\beta$ dependence

up to ~ 30% (negative) correction in the MSSM at large $\tan\beta$

Very clean test of the SM, provided we have reliable independet infos on f_B & V_{ub}

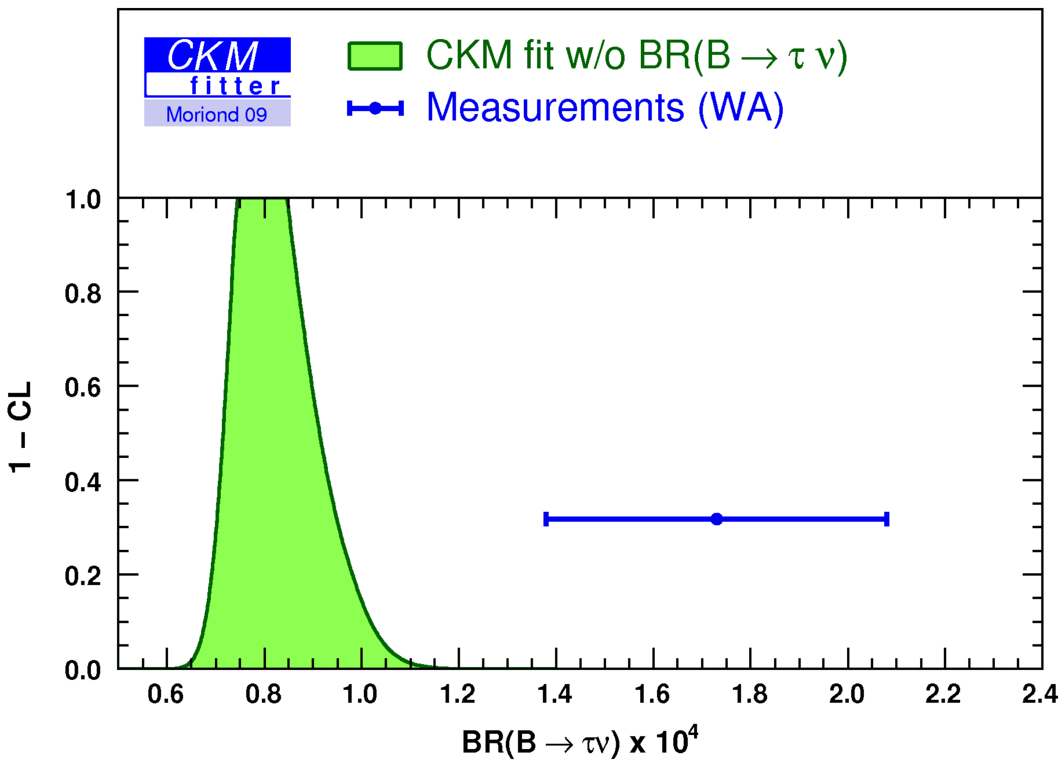
III. $B(B \to \tau\nu)$

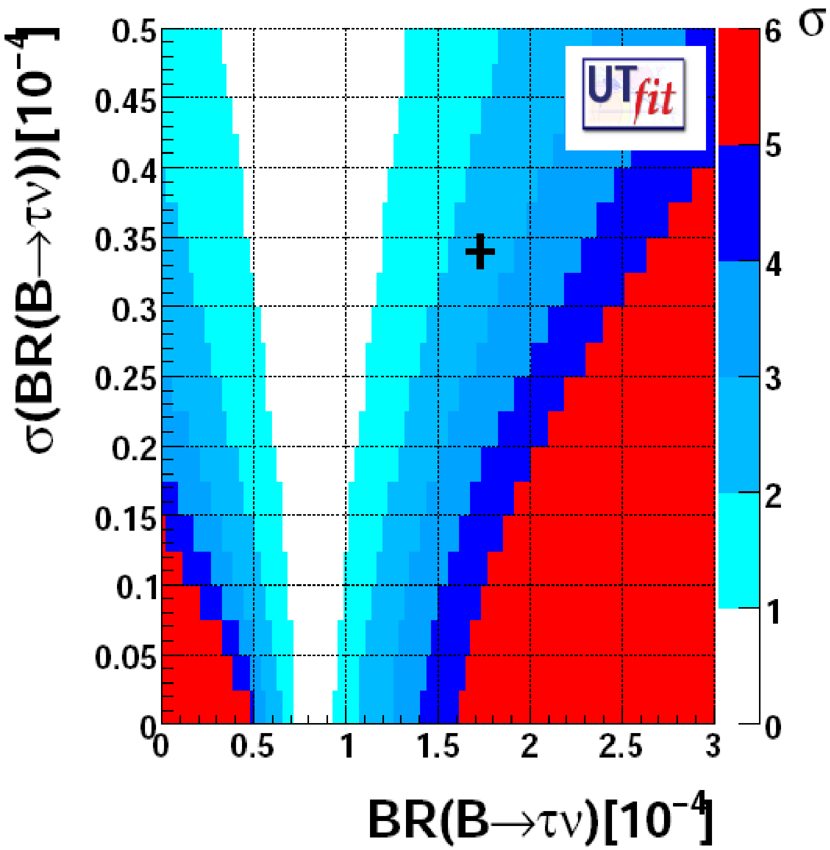
$B(B \to \tau\nu)_{exp} = (1.73 \pm 0.34)\times 10^{-4}$ Babar + Belle '09

$(0.88 \pm 0.11)\times 10^{-4}$ UTfit '09 – global SM fit [5% error on f_b ! - very dangerous]

$B_{SM} = (0.98 \pm 0.24)\times 10^{-4}$ UTfit '09 – no global fit [$f_b = 200 \pm 20$]

$(1.14 \pm 0.28)\times 10^{-4}$ [V_{ub} from UTfit '09 + $f_b = 216 \pm 21$ HPQCD '05]





III. B(B→τν)

$$B(B\to\tau\nu)_{exp} = (1.73 \pm 0.34)\times 10^{-4}$$ Babar + Belle '09

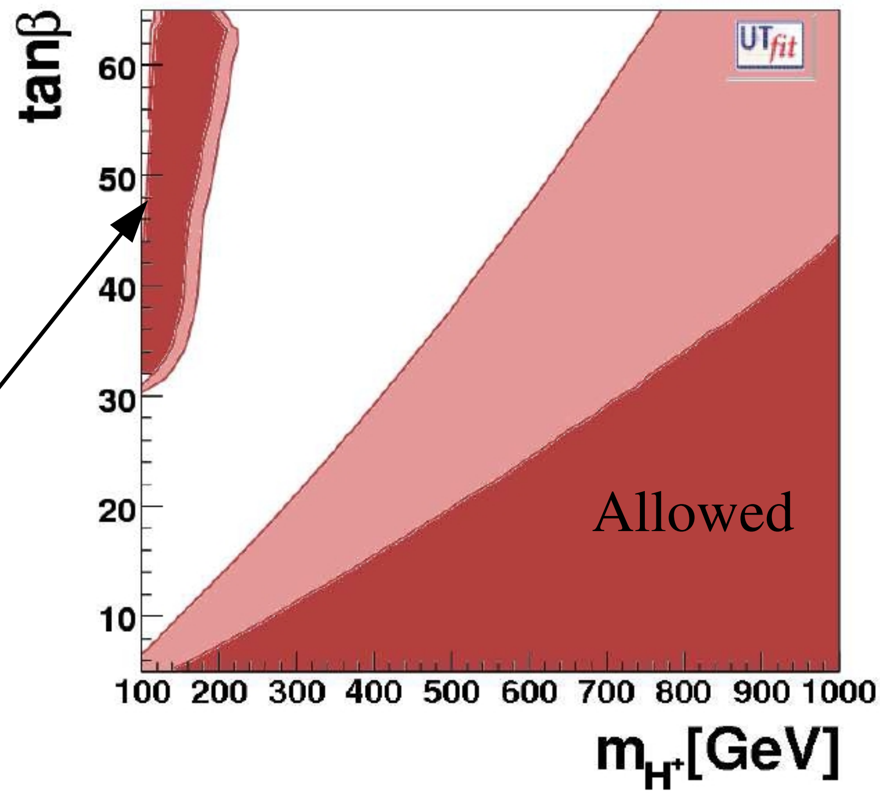
$(0.88 \pm 0.11)\times 10^{-4}$ UTfit '09 – global SM fit [5% error on f_b ! - very dangerous]

$B_{SM} =$ $(0.98 \pm 0.24)\times 10^{-4}$ UTfit '09 – no global fit [$f_b = 200 \pm 20$]

$(1.14 \pm 0.28)\times 10^{-4}$ [V_{ub} from UTfit '09 + $f_b = 216 \pm 21$ HPQCD '05]

Once more, it is too early to claim new physics...

...but it is certainly a stringent constraint on 2HDM & MSSM at large tanβ, with great potential of improvement in the future



Fine-tuned area with large B($B\to\tau\nu$) [excluded by $K\to\mu\nu$]

The "shopping list" of LHCb

High-quality flavour physics requires a good selection...

The "shopping list" of LHCb

- $B_{s,d} \to l^+ l^-$: scalar FCNCs
- $B_s \to \psi\phi$ [$A_{CP}(t)$]: CPV phase in $(b\to s)_{\Delta F=2}$
- $B \to K^*(K)\, l^+ l^-$ [A_{FB}, $R^{\mu/e}$,...]: various precise tests of $(b\to s)_{\Delta F=1}$
- $B \to D\tau\nu$: scalar charged curents
- $B \to DK$: improving γ from clean tree-level processes
- $B_s \to \phi\gamma$ [$A_{CP}(t)$]: right-handed currents in $b\to s\gamma$
- $B_s \to \phi\phi$ [$A_{CP}(t)$]: CPV phase in $(b\to s)_{\Delta F=1}$
- $B \to \tau\mu$ [& other LFV channels]: small chance, but worth to search for

Even being quite selective, the LHCb flavour program is quite wide, with several potentially interesting measurements.

The "shopping list" of LHCb

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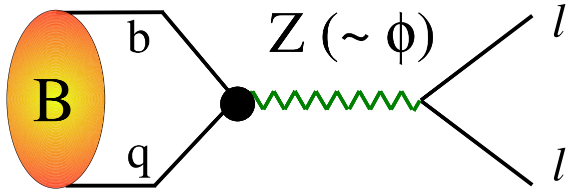
Rating according to the possibilty of finding evidences, or constraining, realistic NP models [*it reflects my theoretical prejudicies: don't take it too seriously...*]

I. $B_{s,d} \to l^+ l^-$

These rare decays are both helicity suppressed and GIM suppressed (FCNC)



longitudinal comp. of the Z (one-loop indiced Z penguin) + realted box amplitude

Excellent probes of models with 2 Higgs doublets (such as the MSSM) at large/moderate tanβ

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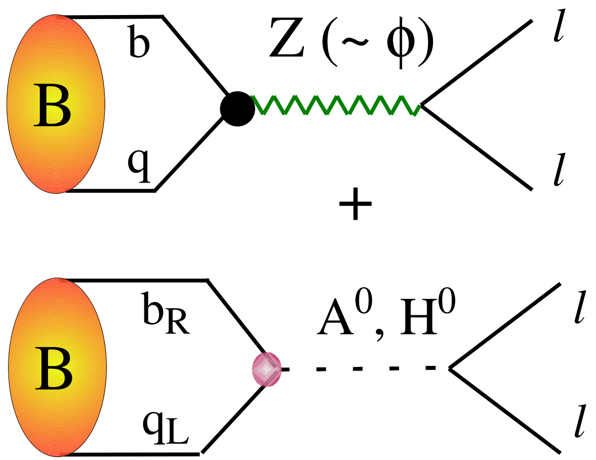
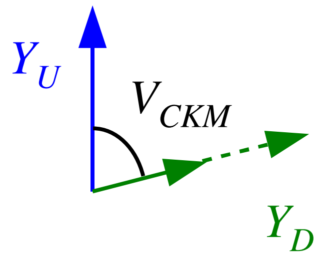


Excellent probes of models with 2 Higgs doublets (such as the MSSM) at large/moderate tanβ

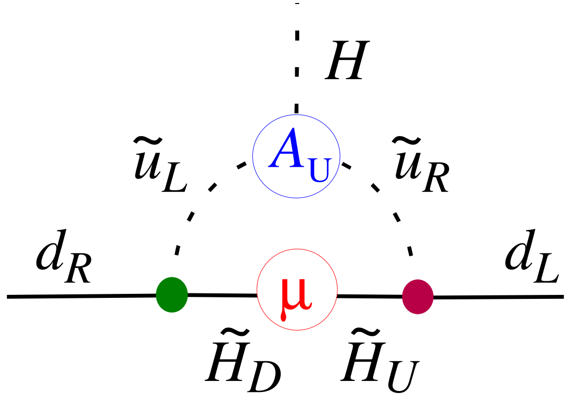


$$\mathrm{diag}(Y_U) = \mathrm{diag}(m_u) / \langle H_U \rangle$$

$$\mathrm{diag}(Y_D) = \mathrm{diag}(m_d) / \langle H_D \rangle = \tan\beta \; m_d / \langle H_U \rangle$$

Even in MFV, the different normalization of the Yukawa couplings induces an effective Higgs-mediated FCNC coupling:

no impact in helicity-conserving processes, but possible large effect in $B \to l^+ l^-$



I. $B_{s,d} \to l^+ l^-$

Present exp. status:

$B(B_s \to \mu\mu) < 4.8 \times 10^{-8}$ (95%CL)

$B(B_d \to \mu\mu) < 7.6 \times 10^{-9}$ (95%CL)

[CDF '09]

SM expectations:

$B(B_s \to \mu\mu)_{SM} = 3.2(2) \times 10^{-9}$

$B(B_d \to \mu\mu)_{SM} = 1.0(1) \times 10^{-10}$

e channels suppressed by $(m_e/m_\mu)^2$

τ channles enhanced by $(m_\tau/m_\mu)^2$

Within the MSSM, wit MFV:

$$A(B\to ll)_H \sim \frac{m_b m_l}{M_A^2} \frac{\mu A_U}{\tilde{M}_q^2} \tan^3\beta$$

Possible large enhancement over the SM but the magnitude of the effect can vary a lot in different SUSY-breaking scenarios

- Th. error controlled by f_B (⇒lattice). Not a big issue if deviations from SM are large, but important to improve in view of future precise measurements
- The $B(B_d \to \mu\mu)/B(B_s \to \mu\mu)$ ratio is a key observable to proof or falsify MFV

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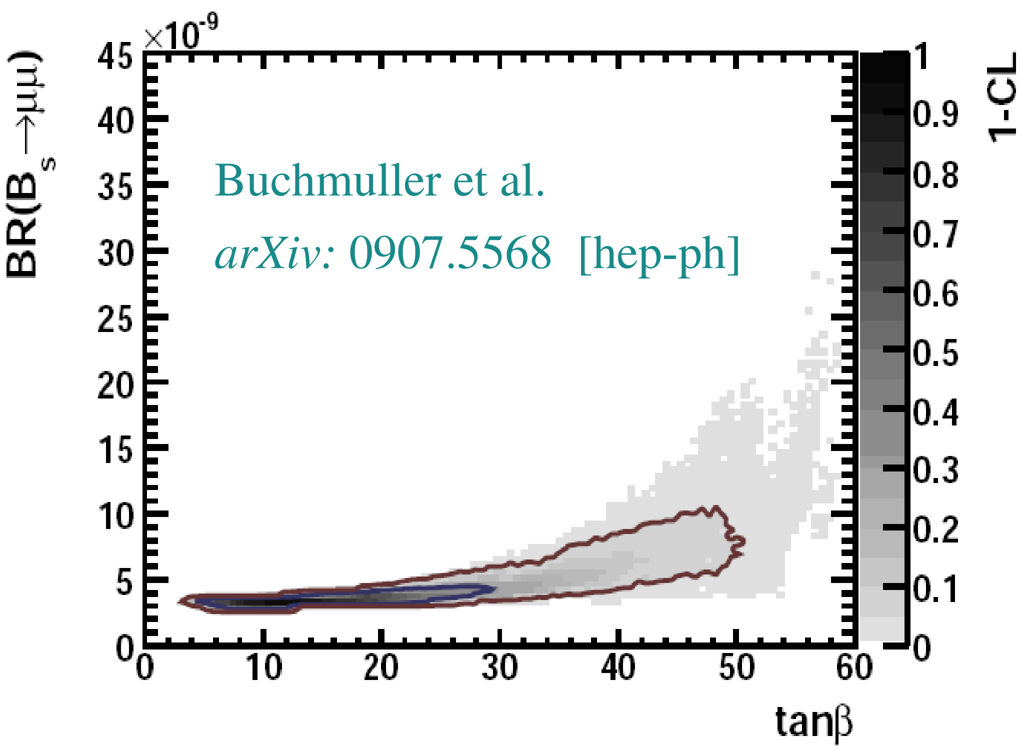
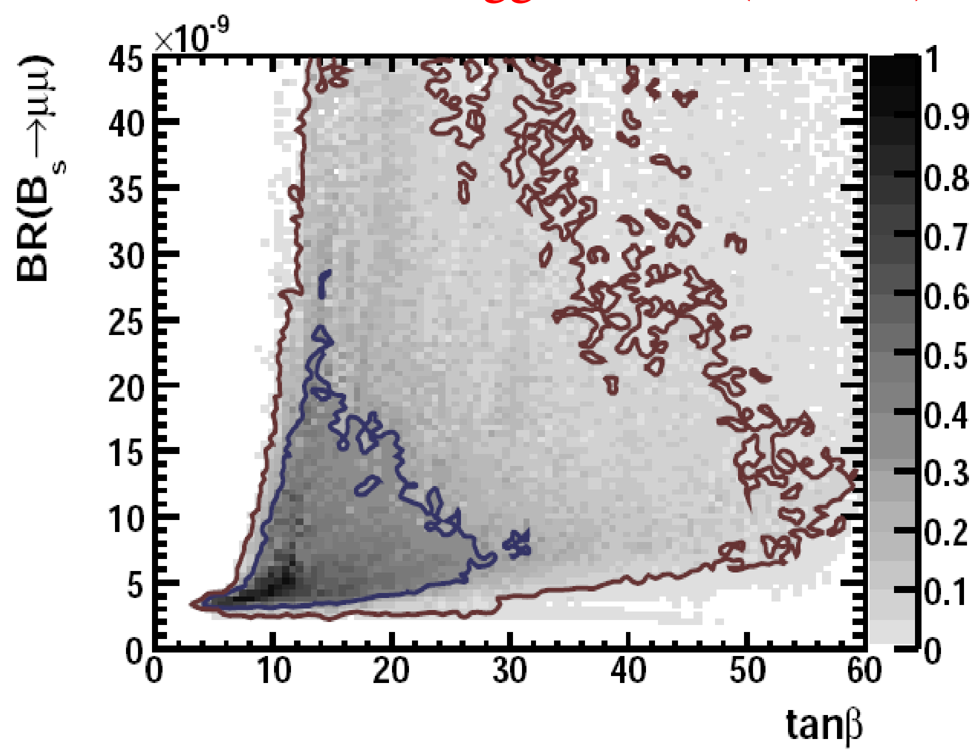
Constrained - MSSM



Constrained – MSSM with non-universal Higgs masses (NUHM)



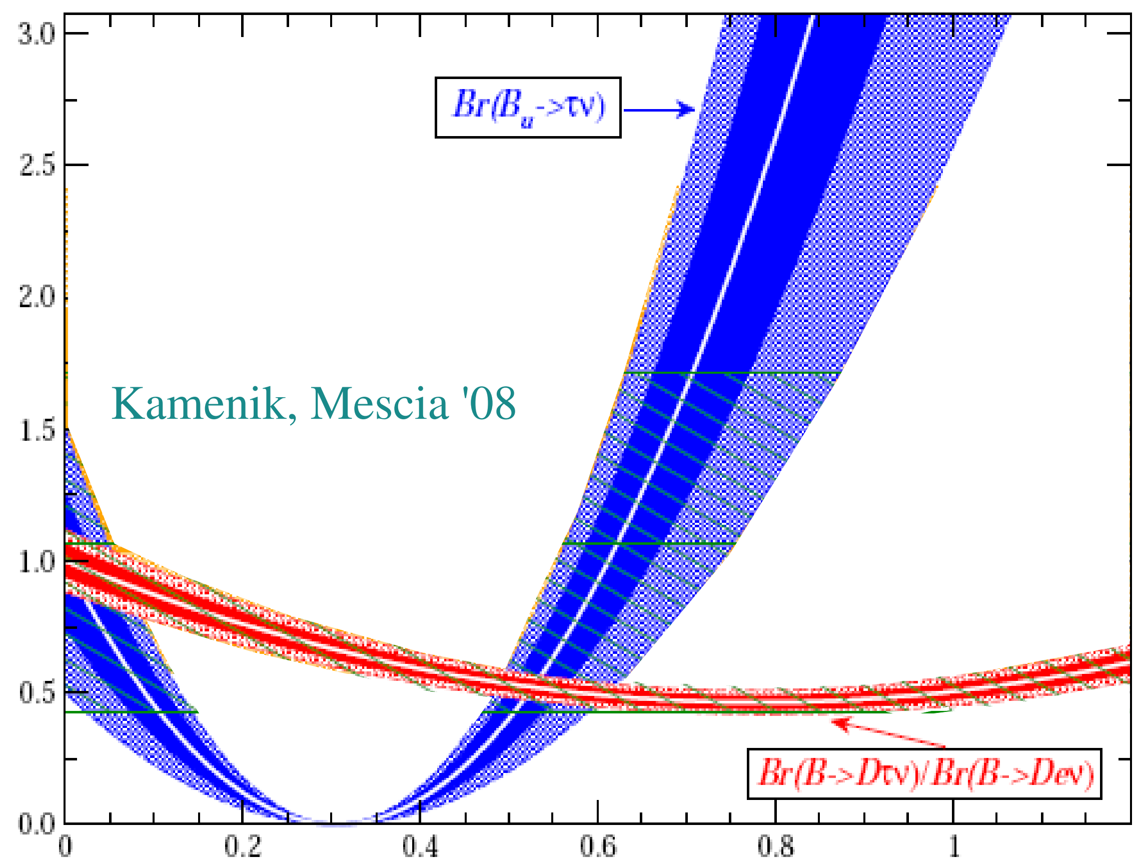
Reaching the SM level would lead to a very significant constraint in the (C)MSSM

II. $B \to D\tau\nu$

The τ in the final state gives a good sensitivity to charged-current scalar amplitudes (large Yukawa coupling) even if the process is not helicity suppressed [typical size: ~30-40% smaller than in $B \to \tau\nu$ (assuming MFV)]

Theory uncertainty (hadronic form factors) substantially reduced (below 10%) if the rate is normalised to $B \to De\nu$ [possible further improvement with Lattice QCD]

$$\left.\frac{\mathcal{B}(B \to D\tau\nu)}{\mathcal{B}(B \to De\nu)}\right|_{SM} = (0.28 \pm 0.02)$$



$$\frac{m_b m_\tau \tan^2\beta}{M_H^2 (1+\epsilon_0 \tan\beta)}$$

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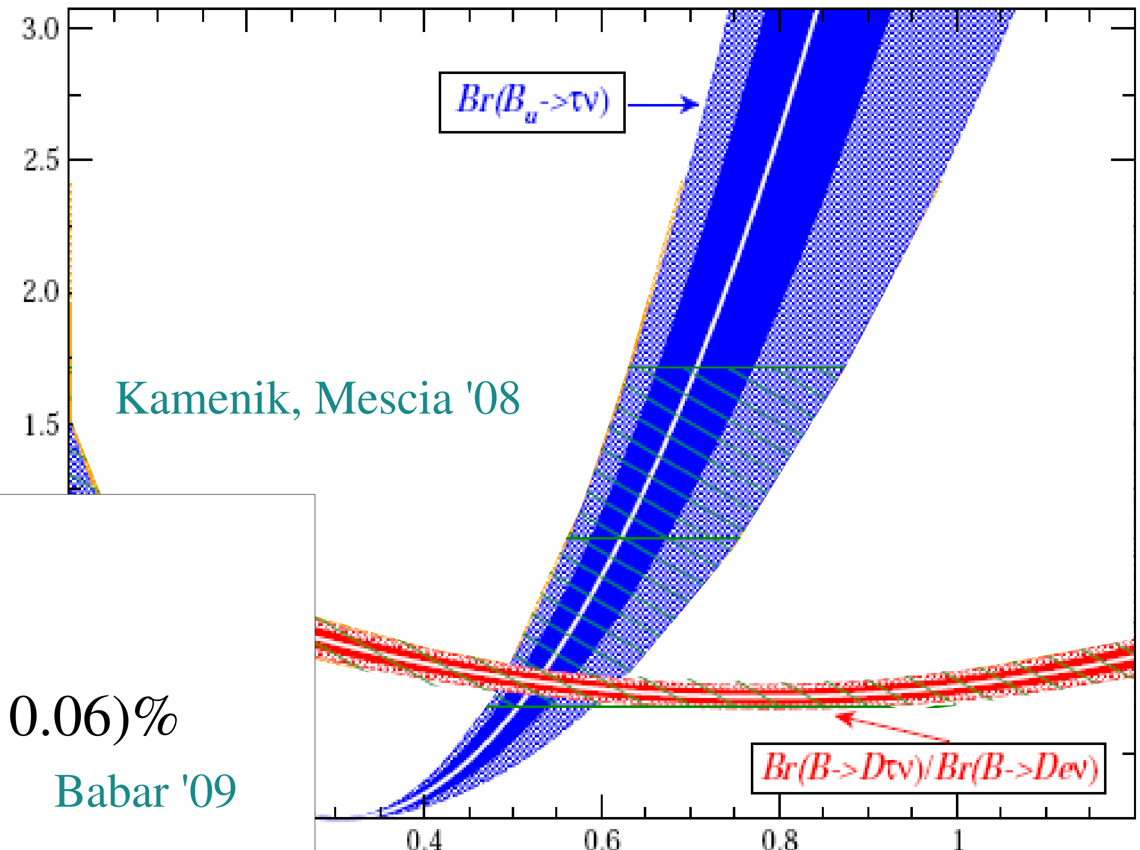


$$\frac{m_b m_\tau \tan^2\beta}{M_H^2 (1 + \epsilon_0 \tan\beta)}$$

$$B(B \to D \tau^+ \nu)_{SM} \approx 0.65\ \%$$

$$B(B \to D \tau^+ \nu) = (0.86 \pm 0.24 \pm 0.11 \pm 0.06)\%$$

Babar '09

$$B(B^+ \to D^0 \tau^+ \nu) = (1.51\ {}^{+0.41}_{-0.39}\ {}^{+0.24}_{-0.19} \pm 0.15)\%$$

Belle '09

III. $B\to DK$

CP violation in charged modes is usually easy from the experimental point of view, but it is hard to be predicted/interpreted from the theoretical point of view [no control on non-perturbative hadronic amplitudes]

$$\Gamma(B^+\to f) = |A_1 + e^{i\gamma} e^{i\delta} A_2|^2 \qquad \Gamma(B^-\to f) = |A_1 + e^{-i\gamma} e^{i\delta} A_2|^2$$

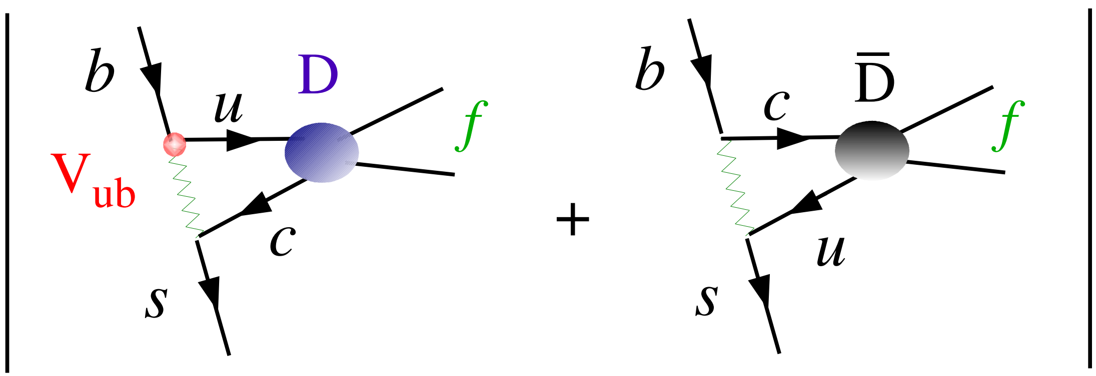
$e^{i\gamma}$: weak phase

$e^{i\delta}$: strong phase

III. *B→DK*

CP violation in charged modes is usually easy from the experimental point of view, but it is hard to be predicted/interpreted from the theoretical point of view [no control on non-perturbative hadronic amplitudes]

A notable exception are the $B^\pm \to D\ (\bar{D}) + K^\pm \to f + K^\pm$ decays



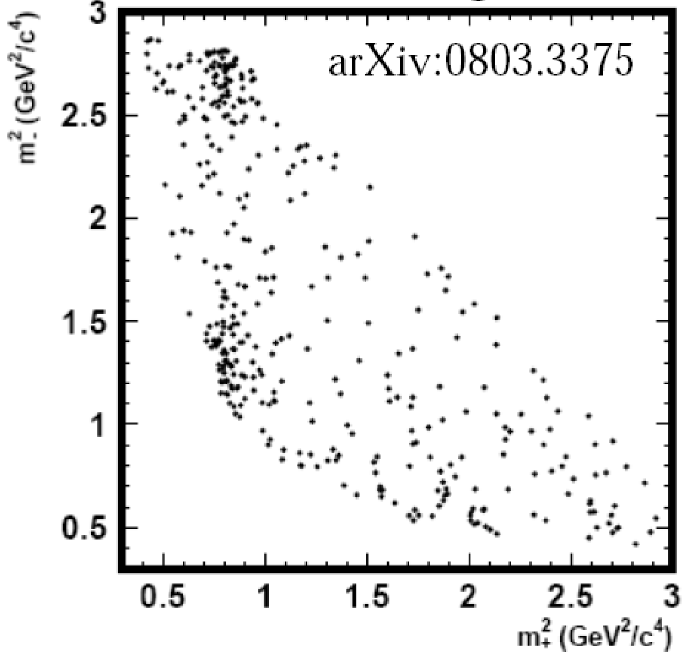
- Neutral D mixing weak phase measured to be small
- Relative weight and phase of the two strong amplitudes measured by looking at CP-conjugate final states

Clean way to extract phase $\gamma = \arg(V_{ub})$:

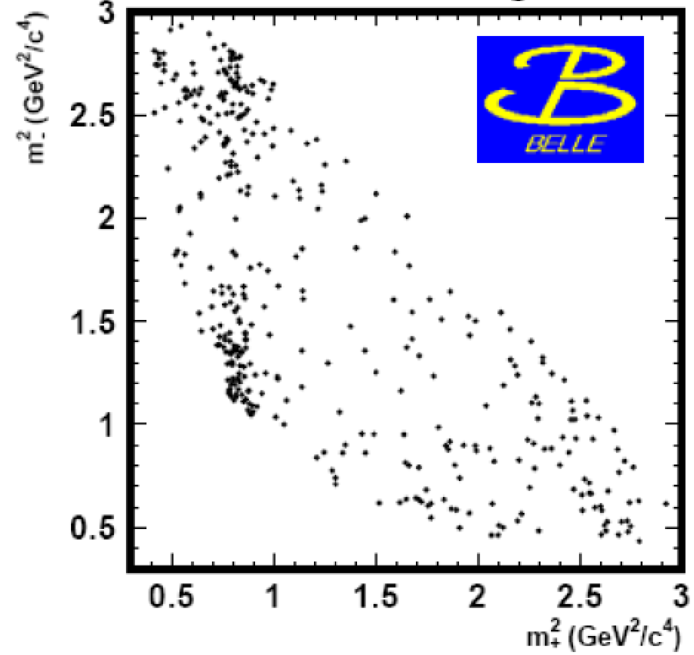
- Gronau-London-Wyler/Atwood-Dunietz-Soni methods: $B^\pm \to (K\pi,\ \pi\pi) + K^\pm$
- Giri-Grossman-Soffer-Zupan method: $B^\pm \to (K_S\pi^+\pi^-) + K^\pm$

full Dalitz-Plot analysis

$B^{-}: \overline{D}^{0} \to K_S^0 \pi^+ \pi^-$

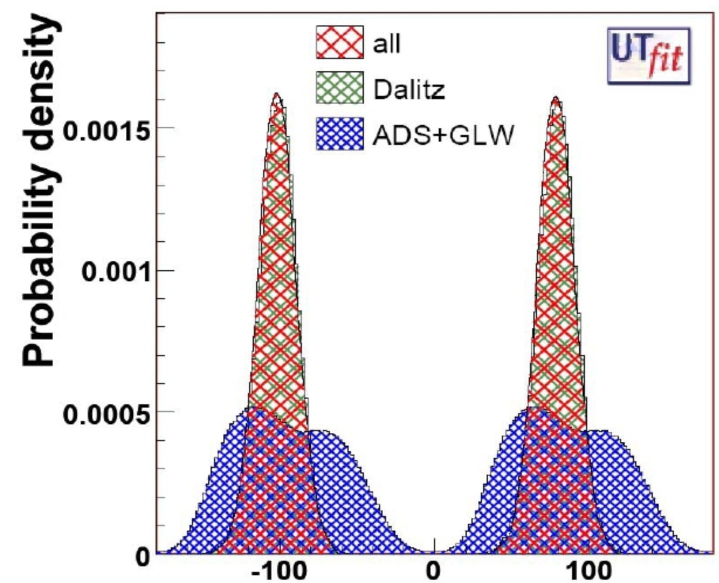


$B^{+}: \overline{D}^{0} \to K_S^0 \pi^+ \pi^-$



Method shown to work at B factories:
no theoretical limitations,
only statistically limited

Clear room for improvements at LHCb



$\gamma(UTFit) = (78 \pm 12)^{\circ}$

Back on the shopping list:

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Conclusions

We learned a lot about flavour physics in the recent past...
...but a lot remains to be discovered !

We have understood that TeV-scale NP models must have a rather sophisticated flavour structure (not to be excluded by present data) but we have not clearly identified this structure yet

↓

Important to continue high-precision flavour physics in the LHC era

- Progress in this field requires a collective effort in several directions: B, τ, K, μ decays, concentrating on the theoretically-clean observables [*mainly leptonic/semileptonic final states*]

- LHCb has the possibility to perform several unique measurements in this context